GREAT BARRIER REEF MARINE PARK AUTHORITY
TECHNICAL MEMORANDUM GBRMPA-TM-16

ACCELERATED REGENERATION OF HARD CORALS: A MANUAL FOR CORAL REEF USERS AND MANAGERS

V.J. Harriott and D.A. Fisk

Sir George Fisher Centre for Tropical Marine Studies,
James Cook University Townsville Qld 4811 Australia

(submitted July 1987)

KEYWORDS: Hard corals, Great Barrier Reef, *Acanthaster planci*, reef damage, transplantation, regeneration

Please address comments or requests for additional copies to:

The Executive Officer
Great Barrier Reef Marine Park Authority
PO Box 1379
Townsville Qld 4810 Australia

ISSN 0817-6094
ISBN 0 642 12032 3
Published May 1995
by the Great Barrier Reef Marine Park Authority

Great Barrier Reef
Marine Park
Authority

PO Box 1379
Townsville Qld 4810
Telephone (077) 81 8811

EXECUTIVE SUMMARY

Coral reefs can be extensively damaged by natural phenomena such as cyclones, man-induced changes such as tourist developments, reefwalking, strandings, and pollution, or by the crown-of-thorns starfish. Estimates of the time required for the natural recovery of severely damaged coral reef systems varies from about five years to greater than 20 years. Management of damaged reef systems may require consideration of options to accelerate the rate at which recovery of the reefs naturally proceeds.

The objectives of the present study were:

- to test, in a field situation, procedures that would accelerate the re-establishment of hard corals in a damaged reef system;
- to compare the rate of natural coral recolonisation to the rate of accelerated coral recolonisation;
- to revise the handbook of methods for accelerated regeneration of corals produced in an earlier study with reference to the field results.

The following report is intended as a manual for those contemplating the regeneration of an area of reef for either management or financial reasons. It is not written as a scientific paper and experimental results upon which the manual is based are confined to technical appendices.

Techniques were developed and evaluated at Green Island Reef which had been affected several years earlier by the crown-of-thorns starfish. A project monitoring the natural regeneration at Green Island was undertaken concurrently and is reported separately, though the results contained therein are referred to where relevant.

The studies showed that the most practical way to accelerate regrowth is by the transplantation of large (>30 cm diameter) coral pieces. The use of large numbers of small fragments of coral (<10 cm length) scattered over the reef to 'reseed' the coral is not feasible because of their high rate of mortality. Large staghorn *Acropora* corals survive transplantation well, grow rapidly, occupy a large amount of space in relation to their weight, and look attractive. Their use for transplants is recommended. Pocilloporid (including 'brown-stem') and faviid (massive or brain-type) corals also survived well and are suitable for transplantation. Branching poritii corals were unsuitable mainly for aesthetic reasons.

Three-dimensional fragments of branching corals (i.e. with plentiful side-branches) survived better than straight pieces because they are raised off the sandy bottom and are more stable. There was little difference in the survival rates of coral pieces that were either attached to the substrate, or were carefully or randomly scattered, under normal conditions. However, in very shallow water or under storm conditions, attached colonies would almost certainly have increased survival prospects.

To minimise environmental stress it is advisable to transplant corals from sites which have a similar depth and degree of exposure to the transplant site. Corals survived for periods of several hours when transported out of water, but shaded. For travel periods longer than two hours, transport in water is recommended.

The effect on the collection site of removal of corals for transplantation was found to be small because relatively few corals are suitable for transplantation. Damage could be minimised by spreading the collection effort over the widest possible area.

Experienced divers, under conditions similar to those encountered during the study, could collect and distribute sufficient coral to cover an area of 10 m^2 with coral cover of 30% in one work hour (excluding travelling time). When costs of labour, boat charter, equipment expenses and travel time are included, coral transplantation can be very expensive.

Conclusions

Transplantation of large numbers of small coral fragments would bypass the initial slow process of recruitment and early growth, but is not considered feasible because of their very high mortality rates.

Transplantation of medium to large colonies or fragments is feasible and corals had a good survival rate. The costs however are very high.

The collecting effort for transplanted corals should be spread out over as wide an area as possible to minimise the impact, and at least 50% of a large branching colony should be left intact at the collection site to regrow.

In most reefs which have a supply of coral larval recruits, natural regeneration of damaged corals should be well advanced in 5 to 10 years after the damage.

Accelerated coral recolonisation is biologically feasible, and when it should be recommended remains an economic and management decision.

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1 INTRODUCTION

In 1981 the Great Barrier Reef was inscribed on the World Heritage List highlighting the importance of the Reef as an area of world significance. The Australian Government has recognised the significance of the region by the establishment of the Great Barrier Reef Marine Park Authority, responsible for management of the Reef. Coral reefs in general have enormous value for a multitude of reasons, including recreational and wilderness values, income-producing tourism, the basis for amateur and commercial fisheries, a source of biologically active compounds, and for protection of adjacent coastlines.

The basic structure of coral reefs is provided by the corals themselves, which not only form the reef, but also provide food and habitat for a multitude of other organisms. The corals are central to the maintenance of the reef community, and there is evidence that when corals are killed, there is migration or death of some of the associated fauna. Fish poisoning (ciguatera) is thought to increase in areas where live coral cover is severely reduced.

Coral reefs are subjected to many forces, both natural and man-induced, that can severely damage the coral communities. They are susceptible to natural events such as cyclones, unusually high rainfall, low tides or high temperatures, earthquakes and volcanoes, as well as to man-induced changes in water turbidity, sediment load, eutrophication by nutrient input, altered salinity and pollution. It is probable that while damage to coral communities from natural factors will continue in the future at current levels, the amount of stress resulting from the activities of man is likely to increase.

If such impacts damage reef communities, management of reefs will require information on methods to both minimise the impact of man, and to produce the most rapid possible recovery from the impact. With respect to the hard coral community, the time scale of recovery following severe damage is dependent on many factors. These include the cause and extent of the damage, the subsequent environmental conditions (immediately after the damage and in the longer term), and the criterion by which recovery is defined (e.g. coral cover, diversity, similarity to original community). Estimates of the time for coral recovery following severe damage vary from as little as three to 10 years to greater than 20 years.

Proper management of reef systems may occasionally require consideration of the option of accelerating the rate of recovery of coral reefs following severe damage. This may be particularly important in areas of significant commercial interests, or in heavily visited areas. Some processes may change the habitat such that it may no longer recover without intervention, for example recruitment of corals may be impossible in areas that have suffered heavy sedimentation from dredging. In such cases, transplantation of adult corals may be the only way that corals could become re-established in the area.

We discuss here methods that could be used to accelerate the regrowth of hard corals in a damaged reef community, and assess the feasibility, practicalities and limitations of such methods. The methods discussed here have generally been developed from the published scientific literature and then tested in a field situation at Green Island Reef, near Cairns on the Great Barrier Reef. The results of our experiments which test different rehabilitation procedures are given in detail in the appendices.

2 BACKGROUND INFORMATION

This text is aimed at the scientific lay person and as such we have tried to present information with a minimum of scientific jargon. However, we include some essential relevant technical information.

Table 1. Families and genera of hard corals on the Great Barrier Reef.

FAMILY	GENUS	FAMILY	GENUS
Pocilloporidae	*Pocillopora*	Fungiidae	*Cycloseris*
	Seriatopora		*Diaseris*
	Stylophora		*Heliofungia*
Faviidae	*Favia*		*Fungia*
	Favites		*Herpetoglossa*
	Goniastrea		*Herpolitha*
	Platygyra		*Polyphyllia*
	Leptoria		*Halomitra*
	Montastrea		*Sandalolitha*
	Leptastrea		*Lithophyton*
	Cyphastrea		*Podobacia*
	Caulastrae	Oculinidae	*Galaxea*
	Oulophyllia		*Achrelia*
	Hydnophora	Pectinidae	*Echinophyllia*
	Pleisastrea		*Oxypora*
	Diploastrea		*Mycedium*
	Echinopora		*Pectinia*
	Moseleya	Mussidae	*Blastomussa*
Acroporidae	*Acropora*		*Cynarina*
	Anacropora		*Scolymia*
	Montipora		*Acanthastrea*
	Astreopora		*Lobophyllia*
Poritidae	*Porites*		*Symphyllia*
	Goniopora	Trachyphyllidae	*Trachyphyllia*
	Alveopora	Merulinidae	*Merulina*
Thamnasteriidae	*Psammocora*		*Clavarina*
Astrocoenidae	*Stylocoeniella*		*Scapophyllia*
Siderastreidae	*Pseudosiderastrea*	Caryophyllidae	*Euphyllia*
	Coscinarea		*Catalaphyllia*
Agaricidae	*Pavona*		*Plerogyra*
	Leptoseris		*Physogyra*
	Gardineroseris	Dendrophylliidae	*Turbinaria*
	Coeloseris		*Duncanopsammia*
	Pachyseris		*Heteropsammia*

2.1 CORAL TAXONOMY

The classification of the common corals of the Great Barrier Reef into families and genera is shown in table 1. Each genus contains one or more species that are sometimes difficult to separate from each other except by specialised coral taxonomists. Only four groups are frequently mentioned in this report - the faviid and pocilliporid families (the latter includes the genera *Pocillopora* and *Stylophora*), and the *Acropora* and *Porites* genera. These corals are abundant on the Great Barrier Reef; in one study at Lizard Island they constituted over 75% of all corals. The common corals are illustrated in figures 1 and 2.

Corals can also be grouped according to their growth forms although these can vary greatly within species. Some common growth forms are illustrated in figure 3. There are several useful books showing coral identifications, including Deas and Domm (1976), Sheppard (n.d.), Veron (1986), and illustrated books on the Great Barrier Reef.

2.2 THE LIFE CYCLE OF CORALS

Coral colonies reproduce sexually, with most releasing eggs or sperm or both into the water during a brief period in spring or summer. The eggs are fertilised by the sperm and develop into small swimming larvae called planulae. The planulae have a free-swimming period of several hours to several weeks before they settle to the bottom to find a suitable site to permanently attach themselves. During the free swimming phase, the planulae are largely at the mercy of water currents, and the length of time spent in the free-swimming stage and the direction travelled by the currents determine where the planula eventually settles. Corals tend to favour sheltered places such as crevices and undersurfaces for settlement, and it is possible that the availability of good settlement places might limit the number of new corals that can settle in an area.

Once established, the coral polyp grows and divides, laying down the hard skeleton that encases and protects the living tissue and forms a colony of many polyps identical to the original settled polyp. A new coral that has survived long enough to lay down a skeleton is called a 'recruit' to the coral population, and the process of adding new corals is termed recruitment. Once the coral colony is large, a second method of reproduction, an asexual process of reproducing new colonies from fragments that break off the original colony, for example during a storm, may occur in some species. The fragments that survive and grow are genetically identical to each other.

Figure 1 (facing page)

Top row: Pocilloporid corals with a bushy growth form.

A. *Pocillopora* sp. ('brown-stem')
B. *Seriatopora* sp. ('needle-coral')
C. *Stylophora* sp.

Bottom row: Faviid corals with a massive growth form.

D. *Favia* sp.
E. *Goniastrea* sp. (brain coral)
F. Close up of *Favia* sp. polyps

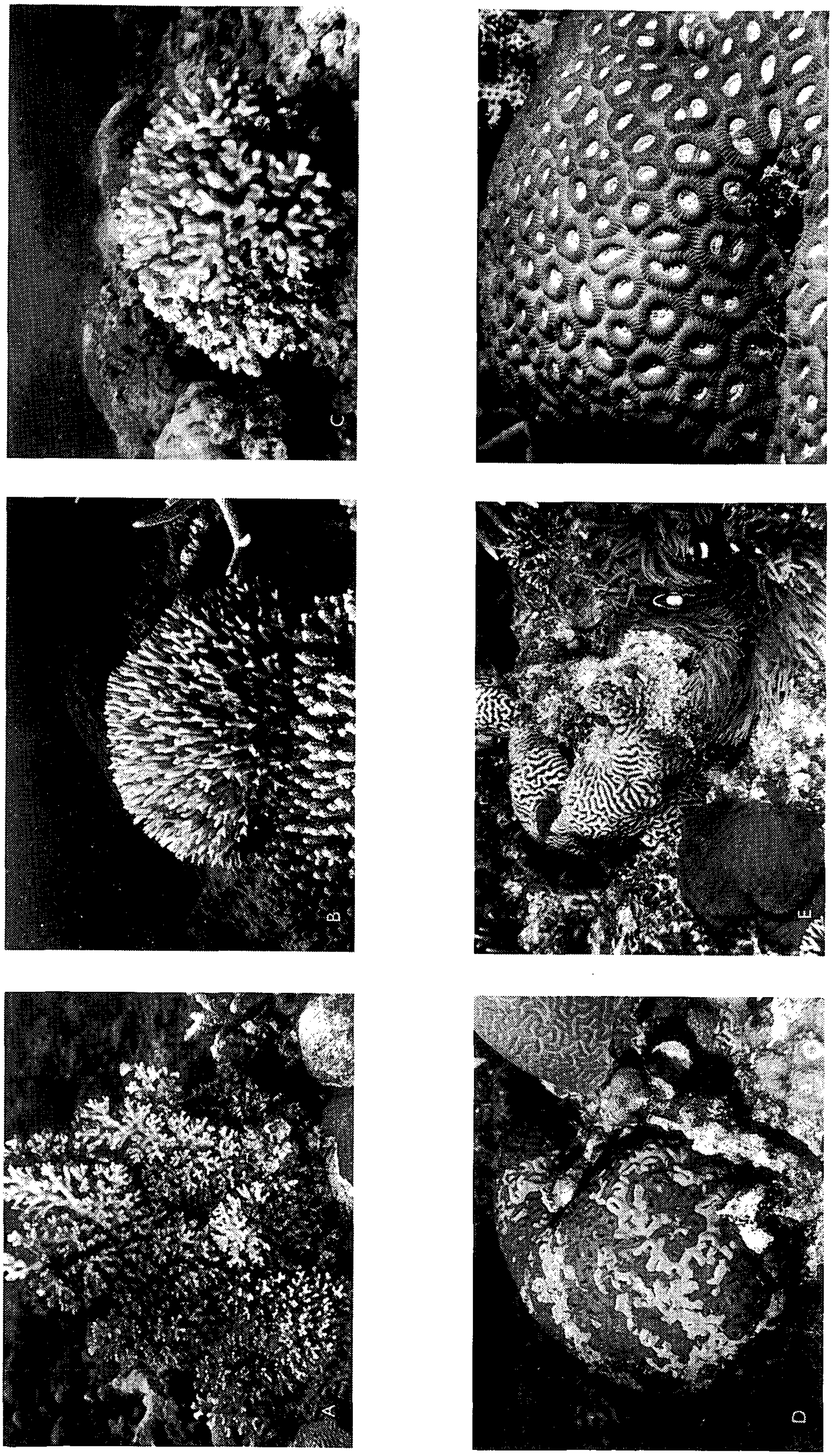
A
B
C
D
E

Figure 2 (facing page)

Top row: *Acropora* sp. corals.

A. Tabulate or plate corals
B. Branching arborescent colony (Staghorn)
C. Close up of *Acropora* sp. branch

Bottom row: *Porites* sp. corals.

D. Massive *Porites* sp. colony (with *Acropora* sp. colony attached)
E. Branching *Porites* sp. (finger coral)
F. Close up of branching *Porites* sp. showing the polyps

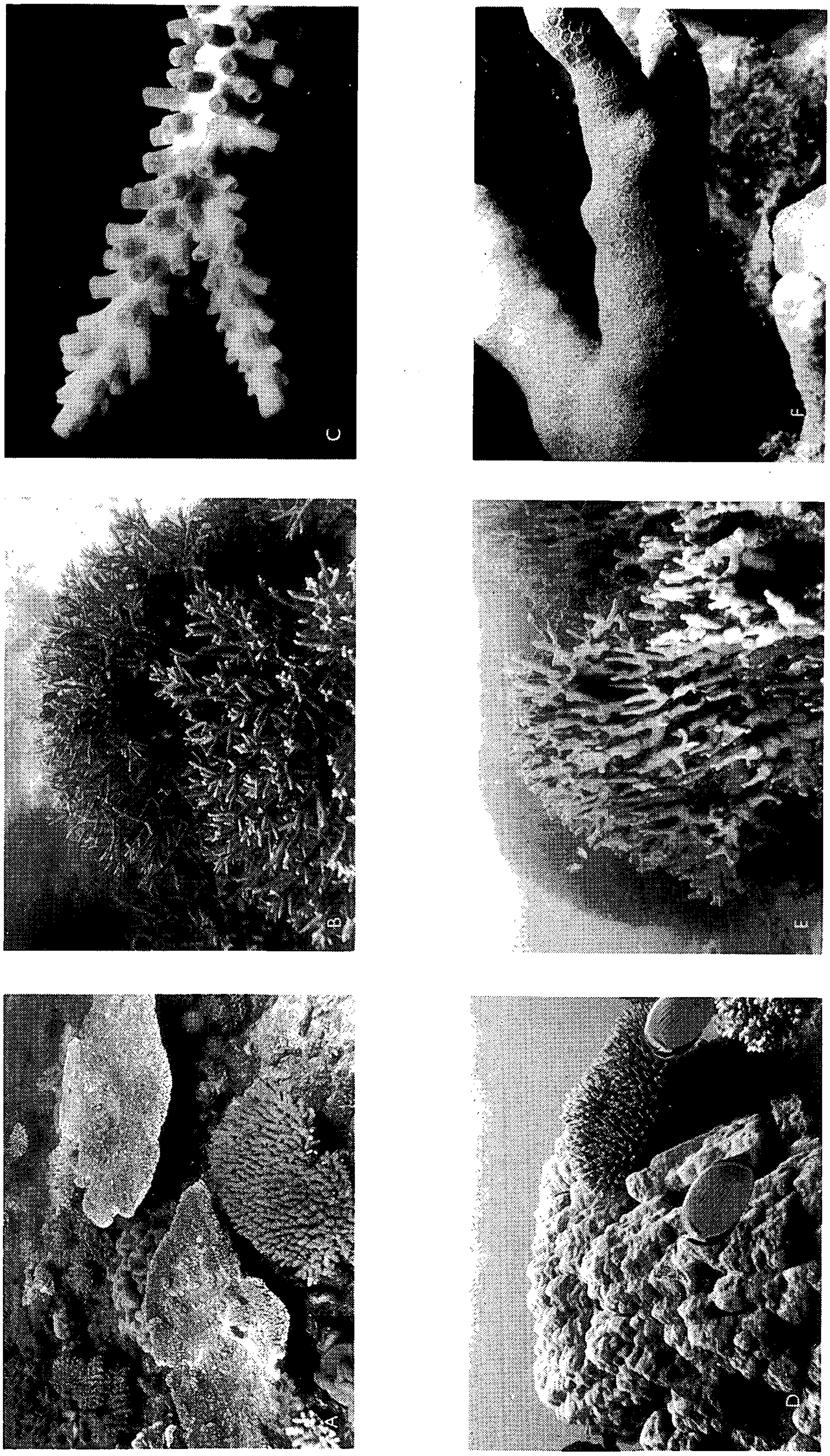
A
B
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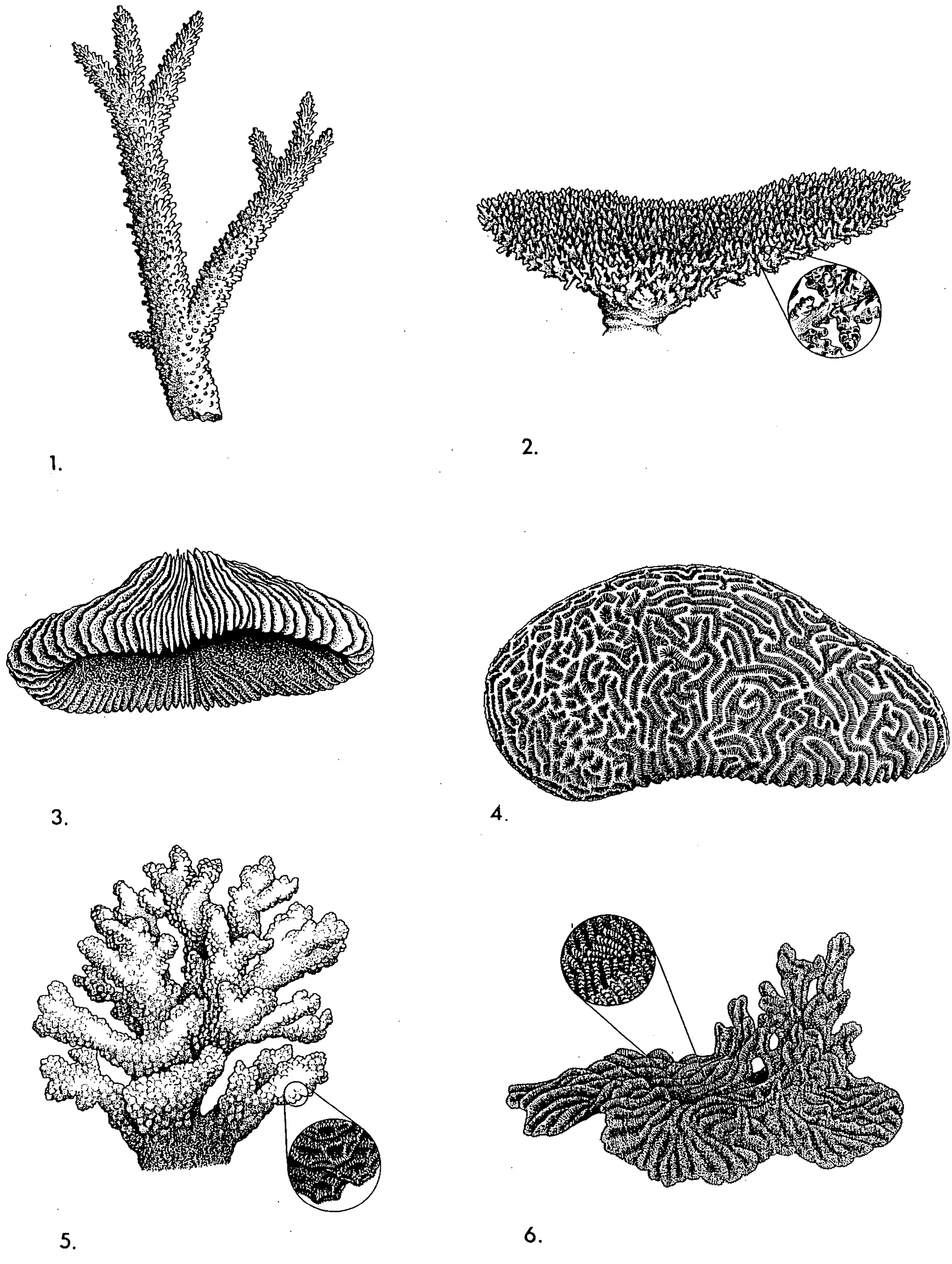
Figure 3. Some growth forms of common coral species on the Great Barrier Reef. (figure courtesy G. Kelly).

1. Branching or staghorn
2. Tabulate or plate
3. Mushroom or solitary
4. Massive or brain
5. Bushy or arborescent
6. Encrusting or foliose



3 DAMAGE AND RECOVERY OF CORAL COMMUNITIES

The causes of damage to reef communities can be discussed under three categories: natural damage, man-induced changes, and damage caused by the crown-of-thorns starfish. The last was considered separately because of the lack of conclusive proof of the causes of population outbreaks.

3.1 NATURAL DAMAGE

The most frequent natural causes of reef damage are severe storms and cyclones, which produce physical damage from water movement, as well as fresh water run-off and high sediment load. Earthquakes, volcanic activity, red tide and unusually low tides and high temperatures are also known to damage reefs. On the Great Barrier Reef extensive bleaching of shallow water coral communities occurred in early 1982. This resulted in high mortality of hard corals, and may have been caused by an unusual combination of weather conditions.

Recovery of reefs from natural damage depends largely on the extent and type of damage. Below a certain level of damage, recovery may be relatively rapid. The recovery rate is also dependent on the species comprising the community e.g. a branching coral community may show extensive damage, but recover quickly as a result of regrowth of surviving fragments.

It has been proposed that where damage is so extensive that few adult colonies survive on a reef, recovery might be delayed by the lack of larval recruits that have to travel large distances from undamaged reefs. Recent evidence indicates that coral larvae may be capable of travelling large distances, and certainly larval periods of at least several days appear to be the rule rather than the exception.

We found in a comparative study of juvenile coral recruitment at Green Island and two nearby reefs that the number of juvenile corals was very much higher at Green Island (which had very low coral cover), than at the other reefs studied (Harriott and Fisk, 1988). This result gives some indication that recruitment of corals may not limit recovery of the coral community, provided the reef is 'downstream' from a source of coral larvae. Coral recruits may also come from corals in undamaged areas of the same reef, and for at least some species and reefs, this could be the dominant form of recruitment.

Extreme low tides have been documented to cause extensive mortality in Red Sea and Pacific Ocean reefs. The rate of recovery of reefs from damage was found at one site to be dependent on whether or not the reef was polluted by oil. On a polluted reef, recolonisation by coral planulae may be inhibited and recovery would proceed slowly.

3.2 MAN-INDUCED CHANGES

Damage to reefs may be acute (one sharply defined event) or chronic (occurring over an extended period), and the two types of damage will have different effects on the community. The period of recovery from an acute event will be similar to that following a natural disturbance, i.e. it will depend on the extent of the damage and the condition of the reef afterwards. Recovery from chronic damage will depend on whether the cause of the damage has ceased, and whether the changes in the environment are long lasting.

3.3 PREDATION BY CROWN-OF-THORNS STARFISH

The history of episodes of crown-of-thorns starfish outbreaks has been discussed many times but there has not been conclusive proof of their causes. Large numbers of the starfish were first reported on the Great Barrier Reef in the early 1960s at Green Island. Over 80% of the coral at Green Island was consumed by the starfish during that period. Starfish populations were subsequently reported on reefs generally to the south of Green Island, but by the late 1970s there were few large populations on the Great Barrier Reef.

A second major population outbreak occurred in the Green Island region in 1979/80. The starfish population was estimated to number several million, and an estimated 90% of the hard coral was killed at Green Island. In 1983/84 large numbers of starfish were present on reefs off Townsville.

The effects of crown-of-thorns starfish on hard corals and subsequent coral recolonisation is relatively well studied. The preferred corals of the adult crown-of-thorns starfish are the branching and plate *Acropora* corals, and to a lesser extent, the massive corals. Factors that affect the rate of recolonisation include the size of the patch damaged, the number of corals or coral fragments left alive after the starfish had left the area, and the availability of coral larvae. Estimates of recovery times (i.e. to coral cover levels the same as before the starfish) are generally in the order of 10 to 50 years.

The definition of recovery will greatly influence the interpretation of recovery times. For example, some species, including many of the plate and staghorn *Acropora* species, are fast growing and recruit rapidly. In a few years following damage a community rich in these species may have a high coral cover but may still lack many of the species present before the damage occurred.

4 APPLICATIONS FOR ACCELERATED RECOLONISATION

There are many circumstances under which the accelerated recolonisation of damaged coral communities might be desirable. Such techniques would generally be applied to reefs frequently utilised for recreational activities (diving, snorkelling, fishing, reef walking) and in particular to reef areas that are the basis for commercial coral viewing or reef interpretative activities. Several examples of cases where accelerated coral regrowth might be desirable are:

1. In areas where coral viewing, glass bottom boats, or reef walking occurs and the coral community is damaged or even naturally depauperate, it could be desirable to increase coral cover to provide an aesthetic reef experience for tourists who pay for such activities.

2. The process of construction of tourist facilities might cause localised damage to the reef community to which the facility was providing access. The rapid recovery of these reef areas would be desirable.

3. If commercial activities (dredging, blasting, release of potential pollutants) damage reef communities, especially where the damage is the result of negligence or poor management, then the responsible agent might take steps to accelerate the return of the community to a healthy state, in a process similar to reforestation programs following mining.

The primary means by which coral regrowth could be accelerated is by transplanting corals from nearby areas with good coral cover. This process is discussed in chapter 5. Other options are theoretically possible but generally impractical, and these are mentioned in chapter 6.

5 TRANSPLANTING CORALS

5.1 SELECTION OF CORALS

a. Corals should be selected from similar habitats to those into which they will be moved, with respect to depth, turbidity, wave action, tidal currents, and degree of exposure to freshwater run-off. Many corals are known to have relatively narrow tolerances for variations in these factors, and selecting the corals from closely matched habitats should increase survival. The most significant consideration is depth, as corals moved to shallower depths frequently bleach, and corals moved to greater depths often have slow growth rates because of the reduced light.

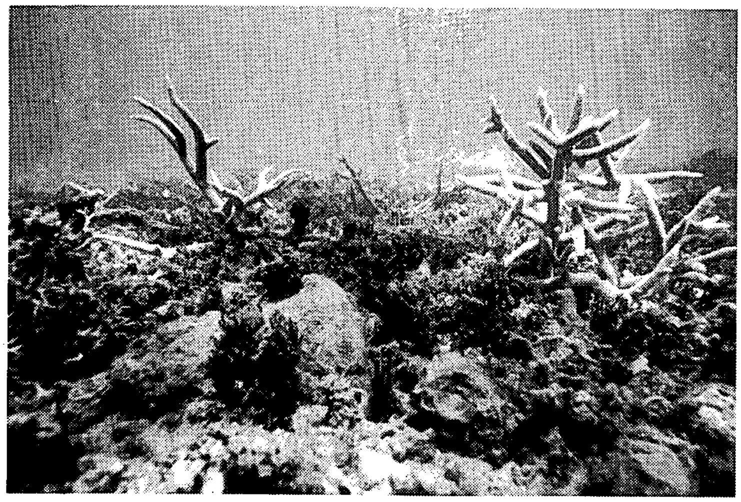
b. In areas where an attractive display is the primary purpose of transplantation, corals will generally be selected for their aesthetic appeal. The ability of the coral colony to contribute to the variety of shapes and sizes in the display, the survival rates of the transplants, and the ability of a colony to grow rapidly after transplantation are also important considerations. From our experiments, we have found that the group of staghorn *Acropora* species are the best suited for transplantation (figure 4a). They provide structural complexity without the heavy weight of massive corals; they survived transplantation well; they are attractive; and they are the growth form most often associated with a typical coral reef. In our experiments they grew relatively quickly.

Pocilloporid corals (see figure 2), in particular the *Pocillopora* and *Stylophora* genera, also survived transplantation well and are attractive, but they are generally smaller than *Acropora* colonies, and grew more slowly in our experiments (figure 4b). Massive corals had the highest survival rates of all coral types in our experiments, but they are difficult to collect, heavy to transport and grow slowly (figure 4c). They would certainly be desirable to include in a mixed species community. We experimented with transplanting branching *Porites* species because they are abundant and easy to collect but they are not a suitable species primarily because their grey colour makes them almost indistinguishable from the background. They also tend to break into small pieces on collection and survival of the pieces is low.

c. To minimise damage to colonies during collection, it is best to select colonies with thin or dead bases in preference to those attached by a large base. Massive corals in particular are difficult to collect because of their broad base. We collected colonies using a hammer and masonry chisel. For collecting the thinner branches of staghorn species, a single sharp hit with a chisel was often sufficient. When branches of *Acropora* corals are collected, the tips of the branches will almost always break, but if the coral survives, the tissue will grow over the broken branch tip quickly (often within a month) and new branches will grow from the tip. In our experiments, tranplanted corals could be easily distinguished from non-transplants because the ends of branches generally showed a rosette type structure where many branches had formed at the regenerating branch tip (figure 5).

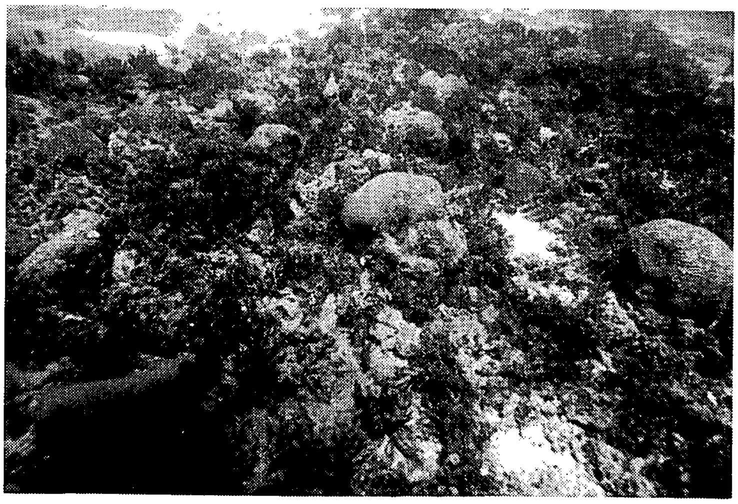
Figure 4. Transplanted corals at Green Island approximately 6 months after transplantation. The site is at about 2 m depth on the backreef.
(a) *Acropora* corals; (b) Pocilloporid corals; (c) Massive faviids.

a.



b.

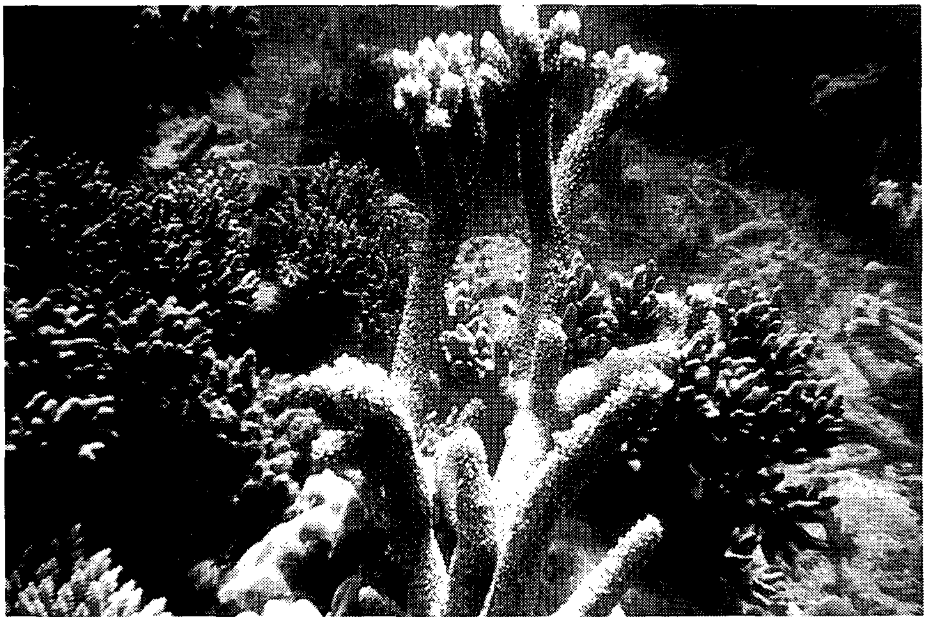
c.



d. A similar collecting effort could be used to collect a small number of large colonies, or a larger number of smaller colonies. The selection of colony size will depend largely on the resources available to the tranplanter (e.g. size of boat, size of display area), taking into consideration the fact that smaller colonies can be spread over a larger area, but do not produce as impressive a display as larger colonies. Below a particular size, survival rate drops sharply for colony fragments. In our experiments, we had good survival for colonies with a longest dimension greater than 30 cm. Survival rates dropped sharply for pieces 10 cm to 25 cm long, and were extremely low for fragments less than 10 cm long. Similar results have been found for fragments of a pocilloporid species.

e. Colony shape is a significant factor in survival of colonies following transplantation. In our experiments with fragments of staghorn coral, we found that selecting branches with a 3-dimensional structure (i.e. plentiful side branches) significantly increased survival rate. A 3-dimensional structure raises part of the coral above the bottom where it is in greatest danger of being buried by moving sand or rubble. It also gives the colony a firmer base on the bottom so that the fragment is less likely to be rolled over or moved to an unsuitable site.

Figure 5. Rosette tip of a staghorn *Acropora* following damage to the growing tip.



5.2 COLLECTION AND TRANSPORTATION

Points to consider in the collection and transportation phase of coral transplantation are outlined below.

a. As little damage as possible should be done to the coral colonies during collection to minimise the areas of dead tissue which might be susceptible to infections, such as 'white and black band disease' reported overseas.

b. Corals should be exposed to the air for the briefest period possible during transplanting. However, our experiments have indicated that survival of all groups of corals exposed to air but out of the sun on the deck of the boat for up to 60 minutes was not significantly different from corals carried in large water containers. Once corals were exposed to air for periods of two hours or more, survival rates dropped progressively. The method selected would depend on the distance between the collection site and the transplant site and the mode of transport. If corals can be transported between sites in approximately 30 minutes or less, the easiest method would be to place the colonies carefully on the shaded boat deck. If exposure period was likely to be over one hour, consideration should be given to carrying the corals submerged in water containers, or to gently splashing water or fine spray on the corals during transport to reduce dehydration. It is recommended that loading of the boat should commence immediately before departure. Establish a collection area under or adjacent to the boat and load when enough is collected.

c. Our experiments showed no significant difference in survival of colonies transplanted in summer or winter, but corals tranplanted exposed to air should preferably be protected from direct sunlight, e.g. with a tarpaulin. Given that corals can be damaged by high temperatures, it may be preferable to avoid exposing corals at the hottest time of the day during summer.

d. Collection and transportation of corals are much easier when weather conditions are calm. In small boats and in wind conditions over 15 knots, there is an increased chance that corals transported on deck will bounce and abrade each other, and possibly break. Most boats can travel faster in calm weather and this would reduce the period of exposure for transplanted corals.

e. It would be possible to transport corals suspended under or alongside a boat in nets or racks, but our tests of this method showed it to be impractical in practice. The boat has to move extremely slowly to prevent loss of colonies and a long journey between reefs could take hours. If weather conditions are not absolutely calm, the corals bounce on each other and are broken. If nets are used, any branching corals become entwined in the nets, are easily damaged, and take a very long time to remove.

5.3 PLACEMENT AND ATTACHMENT AT THE TRANSPLANT SITE

a. Coral colonies may be attached to the bottom, carefully placed on the bottom, or randomly scattered across the area (figure 7). The method of placement will depend on the objectives of the transplantation program, the conditions experienced at the site, and the difficulty of replacing colonies if they should die. We found only a small difference in survival rates for branches of staghorn coral either scattered randomly or carefully placed in the most suitable position. However the appearance of the carefully placed colonies was closer to a natural coral community. The positioned corals also appeared to grow a little faster because the branches were oriented upwards in the natural growth position of a branching coral. Careful placement involved orientation of the coral fragments in their previous growth positions and wedging the fragments as tightly as possible in the substrate. The correct orientation is easily determined by the upward facing polyps and lighter coloured surfaces facing upwards. Careful placement takes very little time and results in a more natural display.

There was also little difference in survival between carefully placed colonies and those attached to the substrate. However in periods of extreme water movements, the differences are likely to be greater. For example, we had a series of experimental transplants in the backreef area of Green Island (at 1-2 metres depth) before Cyclone Winifred. These transplants had good survival rates for a 10-month period following transplantation, but only three of hundreds of unattached transplanted colonies could be found after the cyclone, which produced heavy seas on the leeward side of the reef. Under these conditions, attachment of the colonies would almost certainly have increased the survival rate of the transplants.

If the transplant site is very shallow, or in an area exposed to strong seas or currents, or if it is very difficult to replace corals which are lost in a storm, it would almost certainly be worthwhile to spend the extra effort attaching the colonies.

b. The best method for attaching branching corals in an area containing dead coral is to attach the bases of the living corals to dead branching coral using plastic 'cable ties' (figure 6). These are self tightening, can be attached and tightened in less than a minute on a suitable surface, and come in a range of sizes and colours. We also tried tying the corals on with nylon string, but this was cumbersome underwater and time consuming. It produced an untidy appearance compared to the cable ties and was more prone to loosen with time. It took approximately five minutes to position and tie each coral with string. For both string and cable ties, the coral skeleton had begun to grow over the attachment surface and the ties after about one month, and eventually this growth would give a permanent bond.

c. For massive corals, attachment would be more difficult because of the shape of the coral. Masonry nails or plastic bolts could be attached to the base of the coral, which would then be attached to stakes or wire mesh on the bottom. Alternately, more plugs could be drilled or hammered into the reef rock as attachment points. If the object of the transplanting is to produce an attractive display, the method of attachment must not be unattractive, for example, in scientific experiments people have used old tyres and bedframes for attachments of coral transplants. While practical, these would not improve the appearance on an area. One extra advantage of attachment is that in an area accessible to divers and snorkellers, corals are less likely to be removed if they are firmly attached.

Figure 6. Method of attaching a branching coral to a dead branch using cable ties.

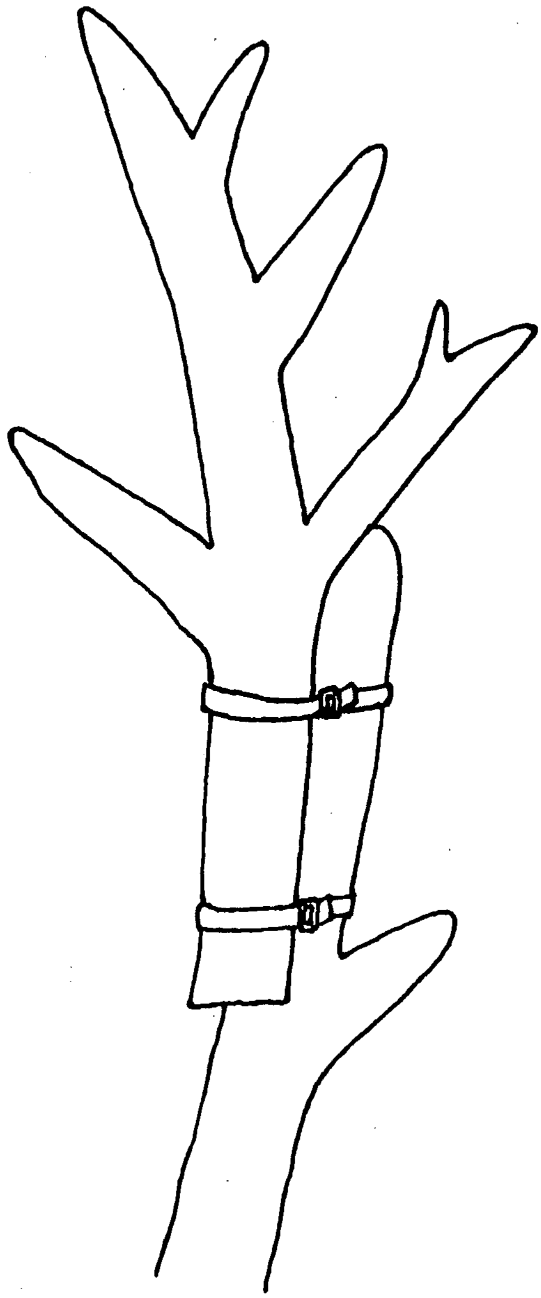
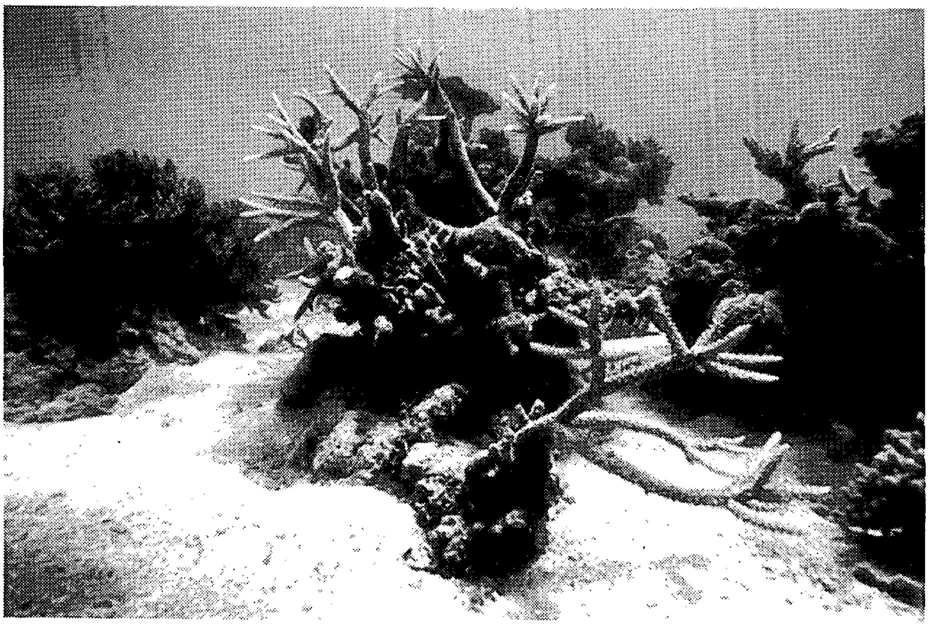


Figure 7. Transplanted corals (a) carefully placed and (b) attached to the substrate. The attached corals have a more natural appearance.

a.



b.

6 ALTERNATIVE METHODS FOR ACCELERATING REGROWTH

Alternative ways of accelerating coral growth were evaluated.

6.1 SELECTION OF CORAL TRANSPLANTS TO MAXIMISE SEXUAL REPRODUCTION

Initial studies emphasised the selection of corals to maximise the possibility that the colonies could reproduce and therefore add reproductive products to the reef. This could be achieved by transplanting well before the breeding season (spring/summer for most corals); by selecting hermaphroditic species (i.e. coral species which have colonies that contain both male and female reproductive organs) and therefore doubling the chances of successful fertilisation; by selecting colonies of reproductive size; by selecting several colonies of the same species instead of one of each of many species, etc.

This is probably unnecessary as recent studies indicate that coral planulae have the potential to disperse widely from their reef of origin. Increasing the amount of reproduction on a damaged reef will not necessarily increase recruitment on that reef, though it may effect a reef 'downstream'. This was confirmed during our study at Green Island (Harriott and Fisk, 1988).

6.2 INCREASING SETTLEMENT SURFACES

The rate of recruitment of juvenile corals may be increased by providing suitable surfaces for coral attachment (e.g. dead coral), or by removing competing animals such as soft corals.

This is considered impractical, and probably unnecessary. At Green Island there were abundant coral recruits on the available settlement surfaces, particularly dead coral which is a favoured surface and is in plentiful supply after damage by crown-of-thorns starfish. When we added dead coral substrate to the reef floor during our experiments, we found they were buried by the shifting sands after several months, long before the limited season in which most recruitment occurs.

There was no clear relationship at Green Island between the abundance of soft coral and hard coral, and it does not appear that algae and soft coral always take over after damage to the hard corals, as some workers have postulated. In cases where the soft coral cover is so high as to cover all available space and prevent the settlement of hard corals, there may be a case for the clearance of some free space. However, keeping in mind the objectives for most programs in accelerating regrowth (i.e. to provide an attractive commercial display), it has been our experience that tourists find areas of soft coral attractive, and there would be little commercial justification for their removal.

It may be desirable to increase surface relief in certain cases. This will be labour intensive but worthwhile if the preferred area of enhancement consists of mainly hard smooth substrate (e.g. large dead *Porites* colonies), or if the area to be regenerated has been sheared smooth by an impact. Increasing surface relief by chiselling or drilling holes in the surface will provide safe sites from grazing for newly settled coral larvae.

Damage to reefs may be acute (one sharply defined event) or chronic (occurring over an extended period), and the two types of damage will have different effects on the community. The period of recovery from an acute event will be similar to that following a natural disturbance, i.e. it will depend on the extent of the damage and the condition of the reef afterwards. Recovery from chronic damage will depend on whether the cause of the damage has ceased, and whether the changes in the environment are long lasting.

6.3 RESTOCKING FROM ARTIFICIALLY RAISED CORALS

It would be possible to transplant onto the affected reef young corals grown from settled planulae in aquaria. This would prevent any damage to the reefs from collection of corals for transplantation, and would increase the chance of survival of the planulae under the protected conditions of the aquarium.

However this was also considered impractical because of the slow growth rate of corals (less than 1 cm across in one year) and high cost of mariculture. Our work has shown that availability of small corals may not be a limiting factor in most cases.

The methods discussed above are probably not feasible as corals are slow growing and have high mortality rates in their young stages. Relying on natural recruitment entails a three to five year delay before the coral community once more resembles a healthy growing one. This period may be too long in some commercial situations.

7 EFFECTS ON THE COLLECTION SITE

There would be little sense in transplanting coral from one reef or site to another if collection of transplants produced extensive damage to the site from which the corals were collected; in effect this is just transferring the site of the damage. It would be preferable to select sites and corals in such a way as to minimise the impact at the collection site.

The possibility of severe damage to the collection site is reduced by the fact that very few species or colonies meet the prerequisites for suitable transplants. Even if all suitable coral was removed from an area, a fairly high proportion of the coral cover would remain.

At the site from which we collected all coral for our transplantation experiments, we measured coral cover before and after a known collection effort. We collected corals from an area approximately 50 m x 50 m, and over one year we removed 430 branches of staghorn coral, 24 pocilloporid corals and 24 faviid corals. The change in coral cover at the site is shown in table 2.

Table 2. Coral cover at the Middle Cay Reef site before and after collection of coral fragments for transplantation.

Coral category	%cover at 11/8/85	% cover at 19/6/86
Hard coral cover (total)	25.6	14.2
Soft coral cover	13.8	11.2
Number of corals (4x30 m lines)	113.0	75.0
Branching *Acropora*	18.0	6.1
Other *Acropora*	1.9	1.7
Pocilloporids	1.1	0.8
Porites	1.9	3.3
Faviids	1.4	1.5

The coral cover changed significantly for the staghorn corals, but cover was still relatively high compared to the other groups. The site still looked like a thriving community and the damage caused by removal of so many branches was not obvious. Where branches had been removed the tips were regrowing rapidly.

We recommend that, in general, corals should be collected over as wide an area as possible. This would reduce the impact at any one site, and depending on the number of corals collected, the change would probably be undetectable. It is certainly possible that in areas of high coral cover, growth of some colonies is limited by competition for space with neighbouring colonies. In such flourishing communities, release from competition by removing some branches or colonies would allow a more rapid growth of other colonies and the space would be quickly occupied.

We also recommend about 50% of each colony of branching coral be left intact at the collection site. The most hazardous life history stage is the recruitment and early growth phase, and if a substantial part of a colony remains, the chances of its surviving and regrowing are much greater than that of a coral planulae attempting to settle on the vacated space.

8 COSTS OF REHABILITATION

A damaged reef might be rehabilitated to a coral cover of approximately 20% to 30% (about normal for a reef), or as low as 10% to 15%. Once a cover of the latter is achieved, the relatively rapid growth rate of the corals free from competition with neighbours would result in a near normal coral cover in one to three years. A costing exercise based on these covers is given in appendix 2.

Costs would vary according to the circumstances and it is not possible to give even approximate estimates. A formula for estimating costs in a range of situations is presented.

Costs
- Boat charter (cost/day x number of days)
- Labour costs (costs/day x number of days)
- Costs of diving equipment and air fills
- Equipment costs - stakes, drills, cable ties, bins, hammers.

The major costs are boat charter and labour. The time required will depend on -

- Initial coral cover surviving
- Projected final cover of coral
- Whether corals must be attached
- The distance to a source of transplantable corals
- The weather conditions and skill of the workers.

The rate at which divers can collect and deposit corals will depend on the skill and experience of the divers, depths, and on the amount of suitable coral at the collection site. We found during the collections for the experiments associated with this study (appendix 1), that in one work hour we could collect and replace on the bottom enough corals to give a cover of 10%-20% over an area of 10 m^2. There were some limitations on the corals collected for the experiments and we could assume that the rate might rise to as high as a 30% cover over 10 m^2 in one work hour. This collection rate is used in the examples given in appendix 2, and will provide a guide for working out total costs when the costs of labour, equipment, boats are known and the area of the site to be treated has been established.

9 ACKNOWLEDGMENTS

We gratefully acknowledge the Great Barrier Reef Marine Park Authority for funding this project. We thank Geoff Kelly for the use of the drawings in figure 3; Paul Fisk, Kathy Means, Neil Boland, Dale McDonald, Mark Earney and others for help in the field. Hayles Pty Ltd gave concessions on their launches, and Queensland National Parks and Wildlife Service (Cairns) assisted with boats several times. Queensland Fisheries Service allowed the use of their storage shed at Green Island, and Nigel Pennington and Jenny Laird provided good liaison with James Cook University.

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APPENDIX 1: EXPERIMENTS ON CORAL TRANSPLANTATION AND ACCELERATED RECRUITMENT, MARCH 1985 TO SEPTEMBER 1986, GREEN ISLAND.

EXPERIMENT 1

AIMS

To measure collection effort and coral cover for 5 types of coral transplanted into marked quadrats.

DESIGN

Approximately 40 2 m x 2 m quadrats were marked with stakes and ropes in the backreef study site at Green Island Reef. This site was on the western edge of the reef and was gently sloping (depth at low tide 2.5-3 m), with a predominantly sand, rubble and calcareous algae (*Halimeda*) bottom.

The transplantation experiment was begun in May 1985 and incorporated seven treatments:

1. addition of fragments of colonies of pocilloporid corals, mainly *Pocillopora damicornis*, with some colonies of *Stylophora pistillata* and *Seriatopora hystrix*

2. addition of staghorn *Acropora* fragments, mainly of the open branching growth form, e.g. *A. formosa*, *A. grandis*, *A. florida*

3. addition of plate *Acropora* fragments including the species *A. hyacynthis*, *A. cytherea*

4. addition of branching *Porites* fragments (*P. cylindrica*)

5. addition of massive colonies (various taxa, mostly faviid species, but including a few massive *Porites*. Corals were of the genera *Favia*, *Favites*, *Platygyra*, *Leptastea*)

6. addition of settlement surfaces (dead coral surfaces)

7. controls (no additions)

Pocilloporid and branching *Porites* colonies were collected from Arlington Reef, and acroporid and massive colonies were collected from Middle Cay Reef. Corals were collected with a hammer and chisel and placed under the boat, with the collection time noted. Immediately before departure, the corals were loaded into filled water containers in the boat. The collecting trips involved a total travel time per trip of between 20 and 60 minutes depending on the sea conditions and the distance to the collecting site.

The number of person-hours devoted to collecting corals for a treatment was determined by a combination of the time available, the amount of deck space available on the boat, and how quickly that space was filled by the corals collected. Collection effort for each treatment is given in table 3. For the addition of settlement plates, effort was defined as the amount of time required to cut up the dead coral surface used.

Transplanted corals were placed into 4 or 5 quadrats, and the collection effort involved per quadrat for each treatment was measured. The different treatments were distributed randomly over the study site. As soon as possible after the transplantation date (after about 10 days because of very strong winds) 3 of the quadrats were mapped to enable an assessment of the number of transplants and approximate coral cover.

In July 1985 we mapped 4 quadrats for each treatment, including the corals that were present before transplantation.

In October 1985 all quadrats were remapped, and surviving coral cover calculated. We intended to extend observations over an 18-month period, but in February 1986 the passage of Cyclone Winifred close to Green Island resulted in the removal of virtually all transplants that had been established and so the experiment was terminated.

RESULTS

Table 3. Collection effort, number of transplants, and mean length of transplanted colonies following transplantation.

Treatment	Collection time (work-) hours	No. quadrats	No. trans-plants in 3 quads.	Fragments/ coll. hr/ quadrat	Colony length (x) (s.d.)
Massives	5	4	23	20	12.7 (4.9)
Pocilloporids	1.0	5	51	28	13.5 (6.2)
Acropora (plate)	0.5	4	32	28	15.4 (12.5)
Acropora (branch)	0.5	5	88	98	17.6 (approx.)
Porites (branch)	1.0	5	184	102	10.9 (approx.)

The branching colonies have the greatest number of transplants per collecting hour, but branching *Porites* fragments were relatively small. They also were difficult to distinguish from the rubble background after transplantation, and for this reason alone, they are unlikely to be suitable for transplantation to area where an aesthetically pleasing display is required.

Within a few months, the vast majority of the coral blocks added to the quadrats to provide settlement surfaces were buried by shifting sand. It was concluded that in this habitat type, added substrate would not accelerate recruitment.

The coral cover in the mapped quadrats 5 months after transplantation are presented in table 4.

Table 4. Coral cover and collection effort for four 2m x 2m quadrats, measured 5 months after transplantation. Results are presented only for coral fragments with a longest dimension greater than 10 cm, as survival of smaller pieces was found to be consistently low.

	Branch. *Porites*	*Pocillop.*	branching *Acrop.*	plate *Acrop.*	massive corals
No. pieces transplanted	112	44	72	24	28
No. pieces surviving	84	39	41	23	27
Surviving coral cover	26%	15%	23%	15%	8%
Collecting time	2.4	2.4	1.6	1.0	1.0
Surviving cover	11%	7%	16%	8%	4%

CONCLUSIONS

The highest survival rate of colonies or fragments was recorded for massive corals, plate *Acropora*, and pocilloporid corals. However the greatest cover per unit effort came from branching *Acropora*. These were easy to collect, occupied large amounts of space, and survival rate was acceptable.

Surviving cover of branching *Porites* was moderate, but the fragments blended with the background and would add little to the appearance of a reef area.

The experiment was prematurely terminated by the damage caused by Cyclone Winifred. As a result change in coral cover in control quadrats could not be determined. Changes over the first 6 months did not appear to be significant. The burial by sand of the coral blocks added to provide settlement surfaces for coral spat demonstrated the limited value of such a strategy in habitats with sandy substrata.

EXPERIMENT 2

AIMS

To further investigate survival of transplanted *Acropora* fragments with respect to fragment size and transport method.

DESIGN

Four branches from each of 9 colonies of branching *Acropora* were collected from Middle Cay Reef. There were 4 treatments:

1. Branches >25 cm long were transported dry on the boat deck

2. Branches >25 cm long were transported in bins of water

3. Branches were broken into pieces 10 to 25 cm long, and transported in bins of water (38 pieces)

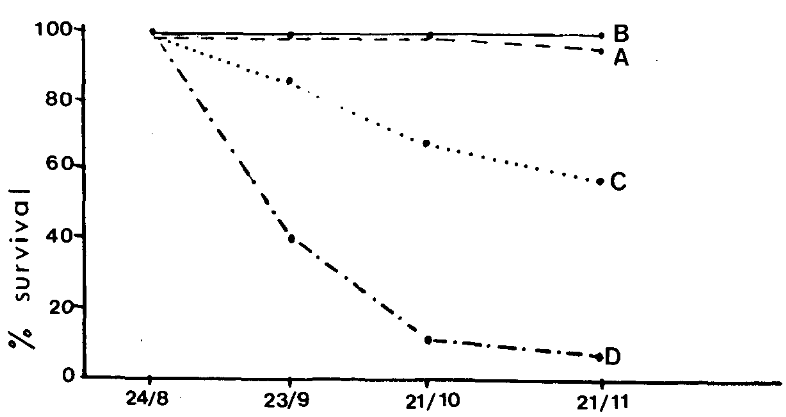
4. Branches were broken into pieces <10 cm long, and transported in bins of water (109 pieces)

Transport time was approximately 40 minutes. Corals were placed in the same backreef study site used in experiment 1.

RESULTS

Results are given in figure 8. There was no significant difference between survival of the corals carried on deck or in bins of water, over the next 3 months. There was decreasing survival rate for smaller fragments, such that survival over 3 months for fragments less than 10 cm long was less than 10%.

Figure 8. Survival of transplanted *Acropora* fragments (experiment 2). A=25cm long, dry on deck (n=9); B=>25cm long, submerged (n=9); C=10-25cm long, submerged (n=38); D=<10cm long, submerged (n=109).



CONCLUSIONS

Transportation of coral fragments exposed to air for short periods does not appear to increase transplant mortality, and mortality rate increases sharply with decreasing fragment size.

EXPERIMENT 3

AIMS

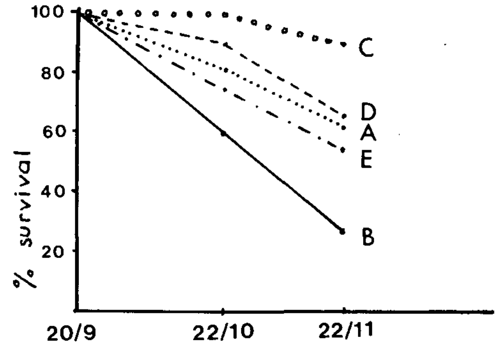
To examine differences in survival rate of branch and unbranched fragments of *Acropora*, and to compare survival rates at forereef and backreef sites.

DESIGN

On 19 and 20 September 1985, we collected 153 fragments of staghorn *Acropora* from Middle Cay Reef. Each fragment was 20 to 30 cm long and was either branched or relatively straight with few side branches. The fragments were carried in bins of water and travel time was approximately 50 minutes. Treatments were as follows:

1. 31 branched fragments placed in forereef site on rubble
2. 30 unbranched fragments placed in forereef site on rubble
3. 31 branched fragments placed in backreef site on rubble
4. 30 unbranched fragments placed in backreef site on rubble
5. 31 branched fragments placed in backreef site on sand

Figure 9. Differences in survival rate of *Acropora* fragments for branched and unbranched pieces and for a backreef and a forereef site (experiment 3). A=branched, forereef, rubble; B=unbranched, forereef, rubble; C=branched, backreef, rubble; D=unbranched, backreef, rubble; E=branched, backreef, sand.



RESULTS

Survival rates for the 2 months following transplantation are shown in figure 9. In both forereef and backreef sites, survival rate for unbranched fragments was less than for branched ones. In the backreef site, survival on sand was the lowest of all treatments, and large areas of surviving colonies were partially buried. The colonies seemed unlikely to survive for long periods. In this experiment, survival rate was higher in the backreef than the forereef site.

CONCLUSION

Survival rate was higher for branched over unbranched fragments, on rubble rather than sand, and in a backreef rather than forereef site.

EXPERIMENT 4

AIMS

To repeat the experiment testing the effect of fragment size on survival rate of *Acropora* fragments (i.e. experiment 2).

DESIGN

Three branches greater than 30 cm in length were collected from each of 10 colonies of staghorn *Acropora*. Transplants were collected from Middle Cay Reef on 12 February 1986, and transported in bins of water (travel time approximately 30 minutes). One branch from each of the colonies formed each treatment as follows:

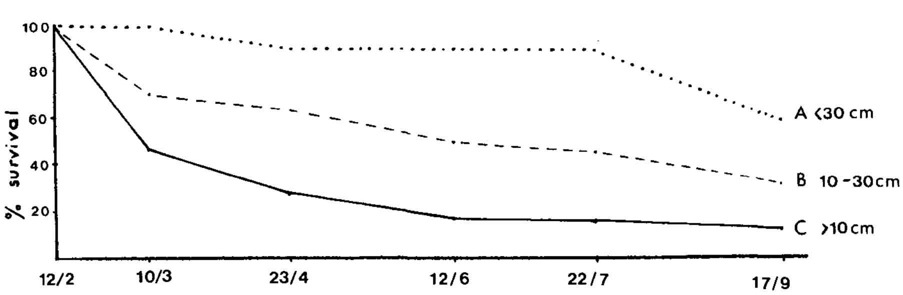
1. Fragments >30 cm long (10 fragments)
2. Fragments 10-30 cm long (28 pieces)
3. Fragments <10 cm long (47 pieces)

Transplants were deposited in the shallow backreef area at Green Island and censused at intervals of 1 to 2 months until September 1986.

RESULTS

Figure 10 shows survival rates for the 3 treatments over 7 months. Results are similar to those shown in figure 8, i.e. decreasing survival rates with decreasing fragment size. After about 2 months following transplantation, survival rate declines only slowly, indicating that most of the mortality due to the transplantation process has already occurred.

Figure 10. Effect of fragment size on the survival rate of branching *Acropora* (experiment 4).



CONCLUSION:

This experiment confirms the results of experiment 2, that small fragments have high mortality rates. It also indicates a falling off in the mortality rate about 2 months after transplantation.

EXPERIMENT 5

AIMS

To examine the effect of exposure to air during transportation on subsequent survival rate for a number of different taxa.

DESIGN

We collected 24 colonies or colony fragments of each of 3 taxonomic groups from Middle Cay Reef on 12 February 1986. They were then transported back to Green Island (travel time 40 minutes) either in bins of water or on the boat deck shaded from direct sunlight by a tarpaulin (12 colonies for each taxa for each treatment). Thus, the treatments were:

1. Branches of staghorn *Acropora* in water bins
2. Branches of staghorn *Acropora* on boat deck
3. *Pocillopora damicornis* in water bins
4. *Pocillopora damicornis* on boat deck
5. Massive faviid corals, in water bins
6. Massive faviid corals, on boat deck

For the *Acropora* and *P. damicornis* transplants, two fragments were generally collected from the same colony where possible so the two treatments contained virtually identical samples. For the faviids, pairs of colonies of the same species and approximately equal size were collected for the 2 samples. Corals were transplanted to the shallow backreef site, and monitored at 1 to 2 month intervals over the next 7 months.

RESULTS

There were no significant differences in the survival of the corals over the next 6 months, for any of the taxa. After 7 months, the number of survivors of the 12 corals originally transplanted for the 'in water' and 'on deck' treatments respectively was 10 and 10 for staghorn *Acropora*, 6 and 11 for *P. damicornis*, and 11 and 11 for massive faviids.

CONCLUSION:

There was no significant difference in survival rate of transplanted corals that can be attributed to transportation either in air or in water bins, when exposure to air was for a period of about 40 minutes. Survival rates of three different coral taxa were also very similar, for a period of 7 months, falling mostly in the range between 83% and 92%.

EXPERIMENT 6

AIMS

a. To compare survival rate of transplants at forereef and backreef site, and of branched versus unbranched *Acropora* fragments (to repeat experiment 3).

b. To check whether survival rate could be increased by either careful placement of the transplanted corals on the substratum, or by attachment of the transplanted corals to the existing reef structure.

DESIGN

We collected 6 branched fragments and 2 unbranched fragments from each of 14 large colonies of staghorn *Acropora* at Middle Cay Reef on 14 February 1986. There were 8 different treatments, each with a sample size of 14 fragments:

1. Branched fragment, forereef site, attached with string
2. Branched fragment, forereef site, carefully placed
3. Branched fragment, forereef site, randomly scattered
4. Unbranched fragment, forereef site, randomly scattered
5. Branched fragment, backreef site, attached with string
6. Branched fragment, backreef site, randomly scattered
7. Unbranched fragment, backreef site, randomly scattered

Corals were transplanted in bins of water to simulate the conditions of experiment 3, and transport time was approximately 30 to 40 minutes. Transplants were monitored at intervals of 1 to 2 months for 7 months.

RESULTS

a. Results of the first part of the experiment are given in table 5.

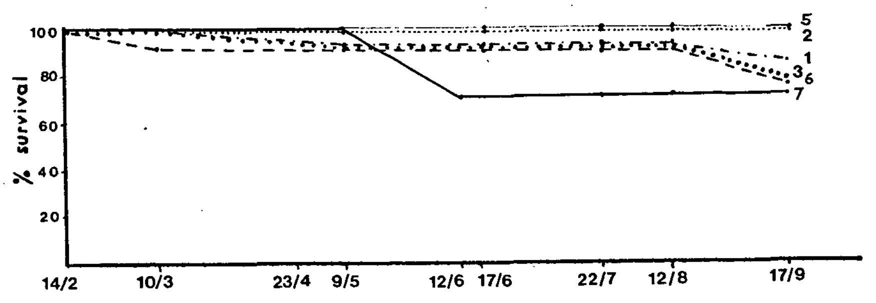
Table 5. Comparison of survival of branched and unbranched *Acropora* fragments in forereef and backreef sites. Initial sample size was 14.

	Unbranched	Branched
Forereef site	2	11
Backreef site	7	10

As was found in experiment 3, there was consistently higher survival of branched over unbranched fragments. There was , however, no clear relationship between location and survival. Unbranched fragments showed higher survival in the backreef site (as was found in experiment 3), while survival of branched fragments was not significantly different at the two sites.

b. Attachment methods. Results are presented in figure 11. There were no significant differences in survival rate that could be attributed to placement or attachment method. There were also no significant differences in survival between forereef and backreef sites for the treatments, with survival for some treatments slightly higher in the forereef and others in the backreef. Survival rates for all treatments ranged between 71% and 100% after 7 months.

Figure 11. Results of experiment 6b, testing the survival rate of transplants of *Acropora* using different methods of placement and attachment at forereef and backreef sites. The numbers on the graph in the figure relate to the treatment number given in the text.



CONCLUSION:

There was good survival for all treatments (apart from unbranched corals) in both forereef and backreef sites. Under the conditions during the study period, attachment and placement method had little effect on colony survival.

EXPERIMENT 7

AIMS

a. To test the effect of increasing periods of exposure to air during transportation on survival rates of transplanted fragments of branching *Acropora* which were carefully placed on the substrate, and if possible to determine the upper length of exposure time that would give reasonable survival.

b. To compare survival rate of corals attached by cable ties with those carefully placed and randomly scattered at a backreef site.

DESIGN

Five fragments with branching morphology were collected from each of 15 large colonies of staghorn *Acropora* at Middle Cay Reef on 15 May 1986. The five treatments (with sample size of 15 fragments) were as follows:

1. Attached with cable ties, exposed 45 minutes
2. Randomly scattered, exposed 45 minutes
3. Carefully placed, exposed 45 minutes
4. Carefully placed, exposed 90 minutes
5. Carefully placed, exposed 120 minutes

All corals were transported exposed to air but protected from direct sunlight. They were placed at the backreef transplant site in slightly deeper water than some of the other experiments (4 m at low tide rather than 3 m). For the corals attached with cable ties, the ties were placed around the base of the branch of the coral and attached to a pre-existing feature of the reef, usually a dead coral. Survival was monitored for 4 months following transplantation.

RESULTS

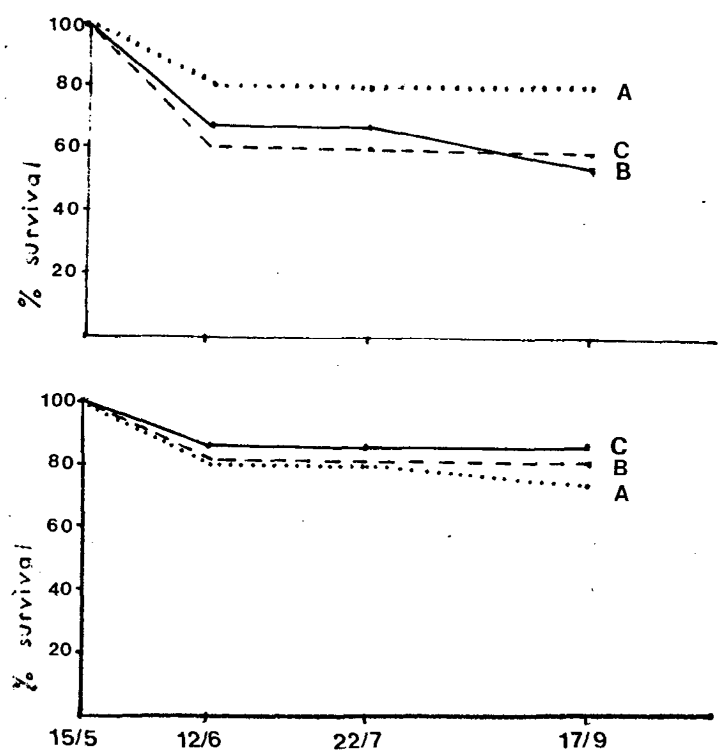
a. Results for variable exposure periods are shown in figure 12a. After 1 month there was a progressive decrease in survival with increasing exposure time, but survival ranged only between 69% and 80%. Survival rate levelled off after 1 month, but some colonies exposed for 90 minutes died between the 2nd and 4th month, so survival was actually slightly lower for the shorter exposure time after 4 months. It does not appear that the limiting time for exposure to air was reached in this experiment, i.e. a significant number of corals (>50%) survived exposure periods of 2 hours.

b. Results presented in figure 12b show that there was no significant effect of attachment method on survival rate for corals treated by the three different methods (carefully placed, randomly placed, tied with cable ties) during the study period. Survival rate levelled after the first month period.

Figure 12. Results of experiment 7, testing

(a) the effect of extending the period of exposure to air during transportation of *Acropora*. A=exposed 45 minutes; B=exposed 90 minutes; C=exposed 120 minutes. All corals were carefully placed.

(b) survival rates of *Acropora* fragments using different placement methods. A=attached using cable ties; B=randomly scattered; C=carefully placed. All corals were exposed to the air for 45 minutes.



CONCLUSIONS

There was a slight decline in survivorship for corals exposed to air for more than 45 minutes, but greater than 50% of corals survived longer than 4 months with exposures up to 2 hours.

Attachment method had little effect on subsequent survival of transplants under the conditions at the study site, confirming the results of experiment 6.

EXPERIMENT 8

AIMS

To determine the maximum period of exposure to air during transportation that would result in an acceptable level of coral mortality for transplants of two different coral taxa.

DESIGN

We collected 45 pieces of *Pocillopora damicornis* and 45 branches of staghorn *Acropora* from Middle Cay Reef on 26 July 1986. The corals were transplanted to a shallow backreef site at Green Island and were exposed to air (but shaded) for different periods. All colonies were placed in their normal growth orientations. Treatments were:

1. *Acropora* exposed 1 hour
2. *Acropora* exposed 2 hours
3. *Acropora* exposed 3 hours
4. *Pocillopora damicornis* exposed 1 hour
5. *Pocillopora damicornis* exposed 2 hours
6. *Pocillopora damicornis* exposed 3 hours

RESULTS

Surviviorship for the 2 taxa over the next 2 months are given in figure 13. In general, colonies of *P. damicornis* survived better than the *Acropora* fragments, although many of the *Pocillopora* colonies had dead tissue over a substantial part of the colony (partial mortality). For both taxa, survival rates declined with increasing periods of exposure. For *Acropora* fragments, survival after 2 months was less than 50% for both 2-hour and 3-hour exposures. Survival of *P. damicornis* after 2 hours exposure to air was over 90%, but survival rate dropped to <55% for an exposure time of 3 hours.

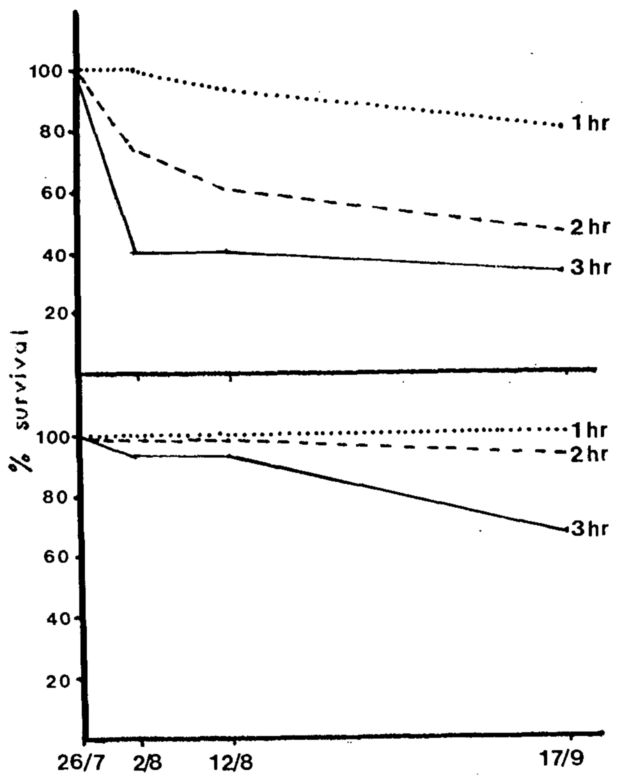
CONCLUSIONS

If transplanted corals are likely to be exposed to air for periods of more than 2 hours during transplantation, consideration should be given to transplanting pocilloporid rather than staghorn *Acropora* corals. Otherwise, it is advisable that periods of exposure be kept to less than 2 hours.

Figure 13. Results of experiment 8 where the effect on mortality of the period of exposure to air of two coral taxa was tested.

a. *Acropora* sp.

b. *Pocillopora damicornis*



APPENDIX 2: EXERCISE TO EXAMINE OPTIONS AND COSTS FOR THE REHABILITATION OF A DAMAGED REEF AREA FOLLOWING A MAJOR PHYSICAL IMPACT.

Damage estimation

In the exercise described here, a structure (for example a large vessel) has been driven across the reef top inflicting direct physical damage on the coral in the region 60m x 150m. In addition to the physical damage, an area twice as large has been affected by the release of on-board pollutants, so the total area affected is 3 x 60m x 150m.

The effects will differ in two regions: the central region damaged physically by the impact; and the outer region damaged by the release of pollutants. Virtually all larger corals and many small corals will be damaged in the central region. Coral cover would be reduced from approximately 30% to 60% on a thriving reef front and top to less than 5%. However it is likely that many smaller corals would survive in the surface relief provided by dips and crevices in the reef structure.

On a backreef area with scattered patch reefs, or on a reef previously damaged (for example by a severe cyclone or by crown-of-thorns starfish predation), the changes are likely to be less dramatic. There might be a reduction in cover from 10% to 25% to less than 5%. The smaller corals that are most likely to have survived starfish predation or cyclone damage are the same ones most likely to survive a severe physical impact.

The associated effects of the release of on-board pollutants are difficult to predict because of the number of variables affecting the outcome. Corals vary in their ability to protect themselves from adverse conditions, for example by covering themselves with a mucus coating. It is likely that reef top corals in general are better able to protect themselves than deep water corals because of the wide range in normal conditions they encounter. Maximum impact would result from release of a highly toxic pollutant immediately before low tide in the middle of a summers day with current patterns subsequently carrying the pollutant across the reef. The coral mortality resulting from the worst scenario described above would probably be in the range of 30% to 80% of corals. However, if the spill of pollutants occurred in the evening on a rising tide, if currents carried the pollutant off the reef and the product was not particularly volatile, the mortality rate is likely to be closer to zero.

Where corals are killed by the effects of the pollutant the major difference from the central affected zone is that the skeletons of the dead corals remain intact. The significance of this factor in recovery is discussed later.

Definition of recovery

'Normal' reefs can vary widely in the range of hard coral cover encountered, both between zones on the same reef and between similar zones on different reefs. For a reef front and reef top used as an example here, coral cover on a thriving reef is likely to range between 30% and 60%. The figure may be higher for a reef shoulder and lower for the sandy outer reef flat. On backreef areas, the coral cover may fall in a similar range as the forereef for a ring reef with a backreef flat and slope, or for a reef with scattered patch reefs there will be large areas of sand between bommies with generally (but not always) lower cover (approximately 25% to 50%).

For a damaged reef to be rehabilitated so that it appears similar to a 'normal' reef, a cover of approximately 20% to 30% would be necessary. A badly damaged reef would be substantially improved by the establishment of a coral cover of 10% to 15%. Once a cover of this level is achieved, the relatively rapid growth rate of the corals free from competition with neighbours would result in a near normal coral cover in 1 to 3 years. These two objectives, that is to achieve a coral cover of about 30%, or a cover of about 15%, are used in subsequent examples.

Estimate of likely recovery time without intervention

Before any attempt is made to re-establish the coral population, it must be determined if the physical structure of the reef is damaged, for example, a channel driven over a reef top may alter drainage patterns from the reef top. Under these circumstances, few corals might survive, and nearby undamaged areas could also be affected. The first step in rehabilitation is to assess and repair any physical damage.

The second step must be to remove or neutralise any remaining traces of released pollutants that might reduce coral survival or recruitment. Such a process would depend on the chemical released and is beyond the scope of this report.

The two techniques for re-establishment of the hard corals are:

(i) transplantation of corals from nearby undamaged areas, and
(ii) methods that accelerate coral recruitment.

A problem arises in the affected central section where the reef surface is most likely sheared smooth. Here there is no place to attach the corals and special supports would have to be hammered or drilled into the reef surface. This would require greatly increased manpower over the option of scattering unattached coral pieces.

One of the limited number of circumstances where accelerated recruitment might be considered is when an impact results in large smooth areas of reef, which are not a favoured settlement surface. By adding relief to such a surface, for example by drilling a series of holes or adding grooves in the surface, it is possible that the rate of recruitment might be greatly enhanced, although such a procedure has not yet been tested in practice. This process would be unsuitable for an area of high sedimentation as the holes or grooves would fill with sand and be unsuitable for coral recruits. It would be unnecessary where good surface relief remains.

Costing exercise

In the exercise simulated below for the purpose of calculating costs, we assume a reef is 60 km from the coast, so a large boat is needed. The cost of the boat charter and a team of 4 experienced divers including their equipment, air fills and use of small boats is estimated conservatively to be $2000 per day. We assume that the distance from the damaged area to the suitable site for collection of transplants can be travelled in less than 15 minutes, and weather conditions are good for the duration of the exercise.

We assume that the coral cover on the area of reef was 50% before the accident. The coral cover following the accident is 0% in the central zone and 25% in the outer zone affected by pollutants (a mortality rate of about 50%). Corals transplanted into the shallow outer zone can be attached to the remaining coral skeletons, while those in the central zone would require special support structures for attachment, for example, stakes or plugs drilled into the reef, or the use of underwater cement. It would be a waste of collecting effort to transplant unattached corals into this zone.

About 25% of the area is covered by water greater than 3 m deep at low tide, and hence corals transplanted into this deeper area need not be attached. The remaining 75% is shallow reef shoulder, crest and flat.

From our studies, we have found that in one work hour, divers can collect, load and unload enough *Acropora* and pocilloporid corals to cover 10 m^2 of reef with a cover of 25%. For the sake of this exercise, we will assume the divers are experienced and can collect fast enough to achieve 30% cover over 10 m^2 in 1 work hour. The divers are unlikely to be able to spend more than 4 hours each per day collecting and depositing corals, as this does not include preparation or travelling time between sites. We estimate the extra time required to attach the corals with cable ties in areas where skeletons remain is an extra 20% above the collecting time calculated, and if special supports or cement must be used, effort will be increased by at least 100%.

We estimate that to cover the entire area with corals at 30% cover would take 430 work days. Assuming a crew of 4 divers, the exercise would cost $215 000.

To cover the same area with corals at 15% cover would require approximately 112 work days at a cost of $56 000. These costs are much lower because no rehabilitation is necessary in the outer zone since cover of surviving corals was 25%. Costs for both exercises would be proportionally much higher if mortality of corals in the outer zone was higher.

A further option is to omit transplantation onto the central physically damaged zone which is the most expensive component of the work, and the area most likely to suffer subsequent coral mortality. If the area was instead treated to optimise natural recruitment by adding physical relief to the soothed surface, this might accelerate natural recruitment at relatively low cost. We estimate that the area could be scored with an underwater drill or hammer and chisel in approximately 8 work days. Combined with transplanting corals to the 15% coral level in the deeper central zone, the cost would be $22 500.

With the exception of a coral viewing site near a tourist resort, it is difficult to envisage a situation where a small section of reef, such as that described for the purpose of this exercise, would be important enough to justify an expenditure of between $22 000 and $200 000 to accelerate a process that would occur, naturally in 5 to 10 years. There is no guarantee that a cyclone the week following rehabilitaton would not destroy the vast majority of the transplanted corals. We believe that under such circumstances the physical structure of the damaged section should be examined carefuly to ensure no changes in tidal flows across the reef that might have wider effects. If not, the case for each incidence of damage must be assessed on its merits, and unless there are pressing aesthetic or commercial reasons for the value of that reef area, the benefits of intensive rehabilitation are small. The area should be monitored at intervals of 1 to 2 years to ensure that the recovery process proceeds as expected, whether or not efforts at rehabilitation are made.